ULTRA-LIGHTWEIGHT AMORPHOUS SILICON SOLAR CELLS DEPOSITED ON 7.5μm THICK STAINLESS STEEL SUBSTRATES

X. Deng, H. Povolny, S. Han and P. Agarwal
Department of Physics and Astronomy, University of Toledo, Toledo, Ohio 43606

ABSTRACT

To significantly reduce the solar cell weight and increase its specific power for space application, we deposited a-Si thin film solar cells on ultra-thin stainless steel (SS) substrates of 15μm, 12.5μm and 7.5μm thick and compared the results with those on standard 5 mil. (127μm) thick SS substrates that we use on a regular basis. To handle these ultra thin SS foils throughout the device fabrication process, we used a carrier method by attaching the ultra-thin SS foils on thicker 127μm SS substrates. We obtained ultra-lightweight solar cells that have similar performance as solar cells on regular 127 μm substrates, with a V_{oc} of 0.887 V, a J_{sc} of 10.8 mA/cm^2, a FF of 68% and an efficiency of 6.5% for cells without back-reflector. These 6.5% efficient, rollable solar cells deposited on 7.5μm thick SS substrates exhibit a specific power of 1.08 kW/kg, significant for space power applications.

INTRODUCTION

Thin film amorphous silicon (a-Si) based solar cells have become attractive alternatives for space power applications due to their low-cost processing and light weight [1,2] as well as their tolerance under high radiation [3]. The weight advantage of a-Si solar cells comes from their low thickness and high absorption constant. However, this weight advantage can only be realized if the substrate on which the solar cells are deposited is also reduced in weight. Several studies have been made in depositing a-Si based solar cells on lightweight substrates. Early in 1988, Hanak *et al* at Sovonics reported the achievement of 250W/kg solar arrays using a-Si deposited on lightweight flexible substrates [1]. More recently, Guha *et al* at United Solar reported 12% efficiency under AM0 illumination for a-Si solar cells deposited on 2-mil thick Kapton substrates [4].

We performed a study to deposit a-Si solar cells on ultra-thin stainless steel (SS) substrates (down to 7.5 μm) for space power applications. In this paper, we report our recent results on the fabrication of a-Si based thin film solar cells on these SS substrates. These thin SS substrates are extremely light weight. In addition, it does not degrade at high temperature, allowing us wider parameter space during the thin film deposition and solar cell fabrication process. Different types of ultra-thin SS substrates are explored and summarized here.

EXPERIMENTAL

Single-junction a-Si n-i-p solar cells are fabricated in this study using an ultrahigh vacuum, multi-chamber, load-locked PECVD system. The device structure used in this study is SS/a-Si n^+/a-Si i/μc-Si p^+/ITO. No current-enhancing back-reflector is used since relative comparison is more emphasized here. Evaluation of the solar cells include solar cell I-V measurement, quantum efficiency measurement and also an estimate of fabrication yield by counting the number of cells functional within a 2"x2" sample.

Three different types of thin SS substrates are explored. These substrates, purchased from Goodfellow Corporation, include:
1) 15-μm thick AISI304 SS foil, as rolled,
2) 12.5-μm thick AISI 321 SS foil, hard; and
3) 7.5-μm thick AISI316 SS foil, as rolled.

Stainless steel substrates, 127 μm thick (5.00 mil.), obtained from ECD, are used for comparison in this study. For a fair comparison, various substrates are put in the same deposition run during the solar cell fabrication. A carrier method is used for handling these thin SS foils during fabrication. In this method, the ultra-thin SS foils are attached to (by wrapping around) thick (127μm) SS carrier throughout the fabrication process.

RESULTS

Table 1 shows the I-V performance of the three most recent deposition runs for a-Si single-junction solar cells deposited on different substrates. All three runs were made using identical deposition conditions for n, i, p and ITO layers. These deposition conditions are the same as those used for the top cell in 11% triple-junction solar cells [1,2] except the i-layer thickness, which is around 200 nm in this study. Four pieces of 2"x2" substrates, mostly of different types, are loaded in each run for comparison.

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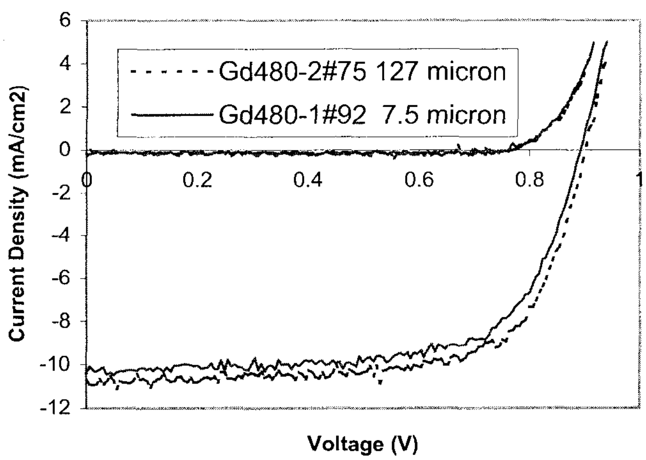
Table 1. Average I-V performance under AM1.5 illumination and yield information for a-Si solar cells deposited on different thin SS substrates.

Device	Substrate	Average I-V performance				Yield	
	Thickness (μm)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Eff (%)	Cells alive	Total cells
Gd479-1	7.5	0.906	10.0	66.0	6.0	5	23
Gd479-2	127	0.891	10.8	68.9	6.7	22	23
Gd479-3	15	0.889	11.0	63.1	6.2	12	23
Gd480-1	7.5	0.887	10.8	68.0	6.5	12	23
Gd480-2	127	0.889	10.9	69.0	6.7	7	23
Gd480-3	15	0.892	10.7	62.6	6.0	5	23
Gd480-4	127	0.864	10.0	65.0	5.6	7	39
Gd481-1	7.5	0.885	10.7	66.1	6.3	11	39
Gd481-2	15	0.895	10.3	64.3	5.9	3	39
Gd481-3	12.5	0.886	10.9	64.1	6.2	10	39
Gd481-4	127	0.889	11.4	66.4	6.7	21	39



Cell	Gd480-2#75	Gd480-1#92
Substrate	127 μm	7.5 μm
V_{oc} (V)	0.901	0.893
J_{sc} (mA/cm^2)	10.7	10.4
FF (%)	70.4	68.7
Efficiency (%)	6.81	6.39

Figure 1. I-V curves of two representative a-Si solar cells deposited on 7.5μm ultra-thin SS substrate and 127μm thick standard SS substrate, showing very similar performance under AM1.5 illumination.

23 cells (or 39 cells) are processed in each 2"x2" sample. By counting the number of cells functionally alive (with FF>60%), we obtained information regarding the dependence of process yield on the use of different substrates. The I-V performance listed in Table 1 is the average performance of the three cells with highest FF in the sample. The uncertainties in V_{oc}, J_{sc} and FF values are approximately 1%, 10% and 2%, respectively. The relatively larger uncertainty in J_{sc} is due to the small size of the solar cells (0.05 cm^2). The J_{sc} values for these solar cells with 200 nm thick i-layers are relatively low due to the lack of a current-enhancing back-reflector.

As we see from Table 1 and Figure 1, the solar cell performances for devices on different substrates are similar. Samples deposited on 127 μm thick substrates generally show slightly higher FF than samples on other substrates in the same run, leading to the highest efficiency. Comparing the thinner substrates, samples on 7.5μm thick substrates outperform those on 15 and 12.5 μm substrates, especially in the FF. Figure 1 shows the I-V curves of one typical cell in each of a 127μm sample (Gd480-2) and a 7.5μm sample (Gd480-1). Both samples show very similar performance within statistical variation.

The fabrication yield, number of cells alive divided by the total number of cells processed, for these samples show that 127 μm thick substrate lead to slightly higher yield. And the cells on the three-types of thin SS substrates show similar yield within statistical fluctuation.

To find out the cause for the dependence of the process yield on the substrate, we examined the different types of substrates using SEM. The SEM graphs show that both the 7.5 μm and 127 μm substrates are smoother while 12.5 μm substrates show more roughness or cracks. The 15 μm substrates appear to be somewhere in between. This may to some extend shed some light on the yield results. We therefore suggest that the use of as-rolled substrates is more appropriate for solar cell fabrication than the use of hardened SS substrates.

To test the robustness of the cells deposited on 7.5μm thick SS, we removed the cells from the carrier and put them on again, the device performance are unchanged. It does not change with normal handlings that our regular solar cells experience.

Table 1 shows only our most recent three runs. The six runs prior to these three runs show very similar results and are therefore omitted for inclusion in Table 1. Although the variation in J_{sc} for different types of cells is within measurement uncertainty at this moment, the data in Table 1 appear to indicate that 127 μm substrate provides a higher J_{sc} than the thin SS substrates. We believe that the difference, if any, would vanish after back-reflector layers, such as Ag/ZnO layers, are deposited on top of the surface. We plan to put Ag/ZnO back-reflector and fabricate high-efficiency triple-junction solar cells on these ultra-thin SS substrates.

Taking the total thickness for the n, i, p and ITO layers to be 300 nm and that for the SS substrate to be 7.5 μm, the specific power for a 6.5% efficient solar cell (Gd480-1) becomes 1.08 kW per kilogram. Such a specific power can be further increased after we fabricate on these thin SS substrates triple-junction a-Si/a-SiGe/a-SiGe solar cells with around 11% efficiency, which have already been fabricated in our laboratory on 127μm thick substrates [5,6]. This high specific power is very important for space power application since it significantly reduces launching cost. In addition, a-Si based solar cells deposited on thin SS substrates can be easily rolled up thus reduce the cost associated with launching volume.

CONCLUSION

Amorphous silicon solar cells have been successfully fabricated on ultra-thin SS substrates with down to 7.5 μm in thickness. Using a carrier method throughout the fabrication process, we obtained ultra-lightweight solar cells that have similar performance as solar cells on regular 127 μm substrates, with a V_{oc} of 0.887 V, a J_{sc} of 10.8 mA/cm^2, a FF of 68% and an efficiency of 6.5% under AM1.5 illumination for cells deposited on bare SS without the use of a back-reflector. It should be noted here that the efficiency value under AM0 illumination should be approximately 20% lower than the efficiency measured under AM1.5 illumination. The solar cell efficiency could be further improved when a back-reflector is used and when a triple-junction solar cell is fabricated on these substrates. The solar cell yield, although slightly lower than those on thicker SS substrates, is however very promising. These 6.5% efficient solar cells deposited on 7.5μm thick SS substrates exhibit a specific power of 1.08 kW/kg, significant for space power application. We have studied the use of various types of SS substrates. The results we obtained so far appear to suggest that the as-rolled AISI316 SS foil is most suitable for the fabrication of a-Si based solar cells for space application.

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